Parsing the "Late Positive Complex": Mental Chronometry and the ERP components that inhabit the neighborhood of the P300.

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Running Head: *P300 Latency and Mental Chronometry*

This is the peer reviewed version of the following article: Dien, J., Spencer, K. M., and Donchin, E. (2004). Parsing the "Late Positive Complex": Mental chronometry and the ERP components that inhabit the neighborhood of the P300. Psychophysiology, 41(5)665-678, which has been published in final form at https://doi.org/10.1111/j.1469-8986.2004.00193.x

Abstract

Falkenstein, Hohnsbein, and Hoorman (1994) suggested that common measures of P300 latency confound a “P-SR” component whose latency corresponds to stimulus evaluation time and a “P-CR” component whose latency varies with response-selection time, thus casting doubt on work in mental chronometry that relies on P300 latency.

We report here a replication and extension of Falkenstein et al. (1994) using a high-density 129-electrode montage with eleven subjects. Spatiotemporal PCA was used to extract the components of the ERP. A centroid measure is also introduced for detecting waveform-timing changes beyond just peak latency.

Componentry-wise, we argue that the P-SR and the P-CR, correspond to the P3a/ Novelty P3 and the P300 respectively. Conceptually, we dispute the proposed distinction between stimulus evaluation and response selection. We suggest a four-stage ERP model of information processing and place the P3a and the P300 in this framework.

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Event-related potentials (ERPs) are manifestations at the scalp of electrical activity associated with the activation of ensembles of neurons in response to a specific event, such as the display of a letter. Many of these ERP components appear to reflect deviance detectors whose purpose may be to alert central executive functions of the need to further evaluate the event (Donchin, Spencer, & Dien, 1997). Analysis of these ERP components provides clues as to the nature and timing of the processes informing these executive functions.

The latency of the P300 component (Fabiani, Gratton, Karis, & Donchin, 1987; Sutton, Braren, Zubin, & John, 1965) has long served as a tool in the study of cognitive function. The P300 is commonly elicited in the so-called “oddball paradigm” in which the subject is presented with a Bernoulli sequence of events that can be classified in one of two categories, and the subject is assigned a task that cannot be performed without classifying the events. If events in one of the two categories appear rarely, these rare events will elicit a P300. Donchin (1981) proposed that the P300 component is the manifestation of a neural system that is engaged when the current model of the subject’s environment requires revision, such as when an unexpected stimulus (e.g., the rare category in the oddball paradigm) is presented (see also Donchin & Coles, 1988).

The well-documented inverse relation between P300 amplitude and stimulus probability means that P300s must be elicited only *after* the stimulus has been categorized. Thus, the latency of P300 will vary with stimulus evaluation and categorization time. That this is indeed the case has been demonstrated by Kutas, McCarthy, and Donchin (1977) who proposed that P300 latency can be used to augment mental chronometry (Posner, 1978). They reasoned that the oft-noted dissociation between RT and P300 latency (e.g., Donald, 1979) is due to the fact that RT is affected by the duration of processes associated with response execution. According to this view P300 latency is a particularly valuable metric of stimulus processing time, as it is relatively unaffected by response selection and execution processes. This hypothesis was confirmed by McCarthy and Donchin (1981) and Magliero, Bashore, Coles, and Donchin (1984) who demonstrated that the latency of P300 covaries with stimulus evaluation time but is largely independent of factors that affect variance of reaction time (RT) through their effects on response selection and execution.

With these data in mind investigators have utilized P300 latency as a tool for decomposing the variance in RT into stimulus- and response-related components. Thus, for example, P300 latency has been used to study issues of attention (Duncan-Johnson & Kopell, 1981), memory (Spencer, Vila Abad, & Donchin, 2000), aging (Bashore & Ridderinkhof, 2002), psychopharmacology (Houlihan, Pritchard, & Robinson, 1996), and brain pathology (Stanzione, Fattapposta, Giunti, D'Alessio, Tagliati, Affricano, & Amabile, 1991).

The utility of P300 latency as a measure of stimulus evaluation time has been questioned by Verleger (1997). Verleger viewed as consistent with his critique the studies by Falkenstein and his colleagues (Falkenstein, Hohnsbein, & Hoorman, 1993; Falkenstein et al., 1994; Hohnsbein, Falkenstein, & Hoormann, 1995; Hohnsbein, Falkenstein, Hoormann, & Blanke, 1991) who claimed that the latencies reported as "P300 latencies" reflect, in fact, the effects of the latencies of two other ERP components. The experiment from this group that they consider as providing the strongest evidence for that position (Falkenstein et al., 1994) presented subjects with an oddball sequence in which a sequence of letters was presented either auditorilly or visually. The subjects were assigned two different response conditions. In the "simple response" condition the subjects were instructed to press a button at the moment of detection, regardless of the nature of the stimulus. In the “choice response” condition, the subjects pressed a button corresponding to the letter (ignoring modality of presentation). Choice difficulty was manipulated by the number of letters (two versus four). Falkenstein and colleagues reported that the stimuli elicited two distinct positive components with a similar latency.

One of these components, labeled by Falkenstein and colleagues the “P-SR” (positivity – simple response), had a modality-specific topography. Auditory stimuli elicited a P-SR with a fronto-central maximum, and visual stimuli elicited a P-SR with a centro-parietal maximum. The authors argued that the P-SR latency reflects stimulus evaluation time (in the sense of identification) because it was elicited regardless of whether or not the subject had to select a response (i.e., it was present in both simple and choice response conditions), and because the component did not increase in latency with increasing choice complexity.

The second component, labeled “P-CR” (positivity - choice response), was modality independent with a centro-parietal topography. The authors argued that it reflects response selection since it was elicited in the choice condition and its latency increased with increasing choice complexity. Falkenstein and colleagues suggested that the failure to observe changes in P300 latency was due to the masking effect of the overlapping P-SR (cf. Verleger, 1997). It is unclear exactly how the P-CR’s topography is supposed to compare with the visual P-SR but Falkenstein and colleagues suggest that the visual P-SR has a more central topography (Falkenstein et al., 1993).

Thus, Falkenstein and colleagues’ critique of P300 latency as a tool of mental chronometry is based on their proposal that two components control P300 peak amplitude and latency. They argue that latency measures of the P300 to visual stimuli actually confound a visual P-SR and a P-CR. The presence of a visual P-SR could confuse measures of the latency by interfering with peak picking. Additionally, the latency measure could be affected by amplitude changes of the P-SR, especially when comparing visual stimuli with auditory stimuli. This view also underlies the argument that different components represent stimulus evaluation and response selection times (Falkenstein et al., 1994; Hohnsbein et al., 1995). In this report we examine this argument in detail, through a replication of Falkenstein et al. (1994) and a detailed analysis of the componential structure of the ERPs. As will be seen below, the picture that emerges from our analysis preserves the value of P300 latency in chronometry.

There have been previous reports that components other than the P300 operate in the time range of the P300 (e.g., Sutton & Ruchkin, 1984). These observations have led some investigators to prefer the label "Late Positive Complex" when referring to the P300 and its neighbors and to treat this ensemble of different components as a unitary entity. However, as we noted in previous reports (Goldstein, Spencer, & Donchin, 2002; Spencer, Dien, & Donchin, 1999a, 2001), it is preferable to examine in detail this so-called "complex" and to parse it into its specific components, each defined by its own scalp distribution and response to experimental variables (Donchin, Ritter, & McCallum, 1978). For example, we have previously presented statistical evidence that the response to novel stimuli in the P300 time window is the summation of a frontal Novelty P3 component and a posterior P300 component (Spencer et al., 1999a, 2001). Similar suggestions have been made previously based on other types of evidence (Cycowicz & Friedman, 1998; Friedman, Cycowicz, & Gaeta, 2001; Verleger, Jaskowski, & Wauschkuhn, 1994). A more complex story has been suggested by a scalp current density analysis or SCD (Yago, Escera, Alho, Giard, & Serra-Grabulosa, 2003), but inferences from an SCD analysis that is based on just thirty electrodes must be viewed with caution (Fletcher, Kussmaul, & Mangun, 1996). Furthermore, as the SCD serves as a high-pass spatial filter which removes broadly distributed components such as the P300 and the Novelty P3 it is not clear that SCD analyses can yield any useful conclusions with respect to the P300 and the Novelty P3. For further consideration of P300 localization issues, see

Dien, Spencer, and Donchin (2003). These difficulties again illustrate that the extraction and identification of ERP components requires a more detailed analysis of the data structure than the identification of peaks over selected intervals. It is evident that the data recorded at any given time point along the ERP epoch may be affected by multiple components. It is for this reason that it is preferable to conduct a systematic decomposition of the dataset as a means to a proper identification of the ERP components.

As we examine the data reported by Falkenstein et al. in the light of the current literature, an alternative hypothesis is that the peak-based decomposition conducted by Falkenstein et al. has led to the identification of "new" components that are more parsimoniously viewed as well-known members of the ERP component structure. Three other frontal positive components with a latency in the range of P300 have been described: the "Novelty P3," the "P3a," and the "No-Go P3." The Novelty P3 was first evoked in experiments with highly novel stimuli such as colored squiggles (Courchesne, Hillyard, & Galambos, 1975) and dog barks (Knight, 1984). Falkenstein and colleagues did not consider this component to be relevant since their studies involved simpler stimuli (personal communication, 2003). The P3a was evoked originally in studies in which a task-irrelevant oddball sequence of tones played in the background while the subject was engrossed in reading or solving puzzles (K. C. Squires, Donchin, Herning, & McCarthy, 1977; N. K. Squires, Squires, & Hillyard, 1975). In one report (Falkenstein et al., 1993), it was argued that the auditory P-SR "contributes to the P3b rather than to the P3a" (p. 157) because the P3a is not seen when the stimuli are equiprobable as in their experiments (N. K. Squires et al., 1975). Finally, the No-Go P3 appears in response to stimuli that indicate the usual response should be withheld (Pfefferbaum, Ford, Weller, & Kopell, 1985). Falkenstein and colleagues suggest it may reflect the contribution of the more frontal P-SR (Falkenstein, Koshlykova, Kiroj, Hoormann, & Hohnsbein, 1995).

Thus, their model proposes six different components: auditory P-SR, visual P-SR, P-CR, P3a, Novelty P3, and the Positive Slow Wave.

Based on developments in the literature since this time, we suggest a simpler taxonomy. On the grounds of parsimony, and given much evidence reviewed briefly below, we suggest that the auditory P-SR, P3a, Novelty P3, and the No-Go P3 may all be the same component (although the No-Go P3 has not been directly compared to the other frontal positivities), allowing this literature to be described in terms of just two components: the P3a and the P300 (with the addition of the Positive Slow Wave under uncertain conditions). We have previously presented evidence that the P3a may be the same component as the Novelty P3 (Spencer et al., 2001); for a similar conclusion see also Simons, Graham, Miles, and Chen (2001). Furthermore, consideration of the Falkenstein et al. 1994 paradigm suggests that the frontal auditory P-SR may actually be a P3a evoked by the recorded voice speaking the letters. Just as a dog bark can produce a P3a even when repeated throughout an experiment (Knight, 1984), so could a recorded voice, although both types of sounds are not so much novel as complex. The remainder of the centro-parietal P-SR and P-CR peaks may be instances of the “classical” P300. Multiple peaks in the P300 can be understood as either the result of a single P300 process with multiple peaks or the result of summation across trials with different peak P300 latencies. In the remainder of this paper we shall use the label P3a, rather than “Novelty P3,” as the latter appellation implies the incorrect impression that events eliciting this component must be “Novel” in the sense of “novelty” used by Courchesne et al (1975). It turns out that while “novelty” may be a sufficient condition for the elicitation of the P3a, it is not a necessary condition (Katayama & Polich, 1998).

As for the argument that the auditory P-SR could not be the same as the P3a because it is evoked by equiprobable stimuli, rarity is only a requirement for unattended tones. While the effects of probability structure on the frontal P3 in attended stimulus paradigms (e.g., Novelty P3 and No-Go P3) have not been fully investigated, preliminary data suggest that highly deviant stimuli presented in an oddball sequence will still elicit the P3a, even when these events are as probable as the standards (Spencer, Goldstein, & Donchin, 1999b).

We tested these contrasting componentry views by replicating the Falkenstein et al. (1994) study and extending it in three different ways: 1) Utilization of a 129-channel system to better differentiate the components than can be done with six channels. 2) Addition of the classic oddball paradigm so that the P300 topography could be directly contrasted with the results of this paradigm. 3) Application of spatiotemporal principal components analysis (PCA; Spencer, Dien, & Donchin, 2001) to make use of cross-channel and cross-time patterns to better separate components.

The two competing views of componentry will be contrasted by determining whether there is evidence for a centro-parietal visual P-SR component that is distinct from a parieto-central P-CR component and a frontal auditory P-SR component as predicted by Falkenstein and colleagues. The contrasting prediction is that there will be a frontal P3a component and a parieto-central P300 component, possibly along with a posterior Positive Slow Wave component. This test will be conducted with the understanding that spatial factors will have a tendency to conflate components with similar topographies so it is possible that the visual P-SR could be conflated with the P-CR even if present; like with other statistical tests, a negative result is suggestive but not conclusive. In this case, the subsequent temporal PCA would not be particularly informative since it would not be able to distinguish between latency changes and the addition of a component. We will examine the results anyway from a methodological interest in contrasting how spatial and temporal PCA cope with latency jitter, which both views agree is present in the P-CR/P300.

Both area and peak measures ignore the substantial degree of component overlap in the ERP waveform (Donchin & Heffley, 1979). Thus, simply measuring amplitudes, or areas, over selected intervals does not suffice to identify known components, or to discover new components. A linear decomposition of the data that relies on the entire period of interest and that acknowledges the multivariate nature of the data is a necessary tool in the componential analysis of the ERP data. This is particularly the case when the data are acquired with a dense array of electrodes that allows a detailed analysis of the structure of the data base (for more extended discussions of linear decompositions of ERP data see Dien, 1998; Donchin, 1966; Donchin & Heffley, 1979; Möcks & Verleger, 1991). It is for these reasons that we examined the present data using the spatio-temporal principal component analysis (Spencer et al., 1999a, 2001). The chief goal for the PCA is to determine if the decomposition of the wave forms will indeed yield two new components that can be accepted as instances of the auditory P-SR, visual P-SR, and P-CR or, as would appear more parsimonious, that waveforms are produced by the activation of the P300 and the P3a components.

Since latency issues are central to the current report, we will also present an improved method for calculating latency. Conceptualize a latency measurement in terms of calculus, dividing up the area under the waveform (for maximum latency) or over the waveform (for minimum latency) into arbitrarily small squares and associating each square with its latency number. A traditional peak latency measurement finds the mode (the latency number most often represented). As in reaction time measures, the mode is useful when one wishes to ignore all but the most prominent feature. For normal ERP data, this is reasonable since one wishes to minimize the influence of small overlapping components or noise but is less of an issue for a PCA virtual waveform, which is designed to remove overlapping activity. If one needs sensitivity to changes in waveform morphology, such as skew, then one needs a measure analogous to the mean. In physics, the standard such measure is the centroid, which provides a "center of mass" measurement.

We therefore implement a centroid measure to determine if a significant shift in the center of “mass” of the P300 waveform is present. The centroid was calculated for the window in each subject average as: $\sum(t * v_t)/\sum(v_t\text{-min})$ where t is a time point in the window and v_t is the voltage at time point t. Min is the minimum voltage in the range of time points being analyzed for each calculated centroid. This has the effect of measuring the area under the waveform (positive centroid). Subtracting the maximum would measure the area above the waveform (negative centroid).

METHODS

The electroencephalogram (EEG) was recorded from eleven students (2 male, 9 female) with a mean age 22, ranging from 18-32. The students, enrolled at the University of Illinois at Urbana-Champaign, volunteered as part of class work. Students were all right-handed, with normal or corrected-to-normal vision, without history of neurological insult, and without current usage of medications with psychotropic effects. Data were gathered using a 129-Ag/AgCl electrode Geodesic Sensor Net (Tucker, 1993), with 12-bit digitizing at 250 Hz. Each electrode was referenced to the Cz site. Amplifier bandpass was 0.1-50 Hz. Each subject attended both a practice session and an experimental session. Missing channels (0.78% of total) were spline-interpolated from neighboring sites (cf. Picton, Bentin, Berg, Donchin, Hillyard, Johnson, Miller, Ritter, Ruchkin, Rugg, & Taylor, 2000).

The experimental design was a direct replication of Falkenstein’s original experiment (Falkenstein et al., 1994), with the addition of two classic oddball conditions. The subjects fixated on a dot in the middle of the screen that was present for the rest of the session. The stimulus was a single letter (A, E, I, or O) that was either presented for

308 ms visually or auditorally. Both the stimuli and the modality of presentation were equiprobable and randomized within a block. Thus, neither the specific character, nor the modality, could be predicted from trial to trial. The letters were .3 by .4 degrees of visual angle and appeared just below fixation. Auditory stimuli were between 60 and 70 dB sound pressure level (SPL), presented binaurally via headphones. The stimulus onset asynchrony (SOA) was 1300 to 2100 ms with an average of 1700 ms. A warning signal sounded at the end of the trial (900 ms after the stimulus) if the subject did not respond by the reaction time limit (see below).

There were two primary tasks. In the “choice” condition, the directions were for the subjects to press one of four buttons corresponding to the letter as quickly and accurately as possible. In half the blocks there were only two letters (half with A & O and half with E & I) and in the other half all four appeared. Each block contained 176 stimuli. The warning signal was triggered if the subject did not respond by 500 ms for the 2-choice condition and by 580 ms for the 4-choice condition. The subjects were instructed that they were to respond fast enough to prevent the warning signal from occurring; even it meant that their error rates increased. Thus, speed was given a higher priority than accuracy. In the “simple” condition the subject simply pressed a single button with the right index finger regardless of the stimuli. Each block contained 80 trials. The warning signal was triggered if the subject did not respond by 280 ms. The subjects were instructed to try to respond even before the letter offset.

In addition, there were two oddball blocks, one for auditory stimuli and one for visual stimuli. In the oddball blocks only two stimuli were presented (80% E and 20% I). For one block both stimuli were auditory and for one both were visual. The task was to press a button to the rare oddball stimulus as quickly and accurately as possible with the right index finger. No warning signal was sounded. There were 160 trials for each oddball task. The SOA was the same as for the main tasks.

The EEG channels were corrected for vertical and horizontal eye movements (Gratton, Coles, & Donchin, 1983) using the channels above and below the right eye for vertical movements and the channels on the outer canthi for the horizontal eye movements. The averages were digitally filtered (0-17 Hz) and baseline-corrected. The data presented have been re-referenced to a mean mastoid reference.

PCAs were conducted using the PCA Toolbox[1], a set of Matlab routines that are available from the first author upon request. A covariance matrix was used so that the solutions would be most influenced by more active variables (channels for a spatial PCA and time points for a temporal PCA). A promax rotation (without the Kaiser correction option) was used to rotate the results to simple structure (Dien, 1998; Hendrickson & White, 1964). Since mixing qualitatively different ERPs in a PCA can result in distortions, specific components were mostly excluded from the analysis by entering only the time points from 200 to 800 ms. For example, if there is an auditory component and a visual component with similar topographies, they may be conflated together, resulting in a factor that does not exactly correspond to either topography. While the sensory components are not of interest in the current dataset and would not be examined anyway, it is possible that some such distortion could propagate into the epoch of interest via components extending into the P3 range.

Repeated-measures ANOVAs were conducted with four factors: modality (auditory, visual), task (choice, simple), stimulus (2-choice, 4-choice), and electrode (Fz, Cz, Pz). The Geisser-Greenhouse epsilon correction (Geisser & Greenhouse, 1958) was utilized to modify the p-values. For effects involving the electrode factor, a follow-up ANOVA was conducted with each condition normalized to unit length to verify the topographical effect (McCarthy & Wood, 1985). If the topographical effect was confirmed, only the normalized analysis is reported. If the topographical interaction was not confirmed, then the unnormalized analysis is reported and the interaction with the electrode factor is ignored. Although this normalization procedure has been recently criticized (Urbach & Kutas, 2002), for a defense of this technique see (Dien & Santuzzi, in press).

RESULTS

Overt responses

Median reaction times (RTs) were calculated using only trials with correct responses. A repeated-measures ANOVA was conducted with three two-level factors: modality (auditory, visual), task (choice, simple), and stimulus (2-choice, 4-choice). As can be seen in Table 1, results were quite comparable to those obtained by Falkenstein and colleagues. As in the original experiment, the F-ratios were quite high because the task is designed to minimize variability in the reaction times. The choice RTs were much longer than those for the simple task: task, F(1,10)=1256, p<.0001. This was particularly the case for auditory stimuli: modality * task, F(1,10)= 14.6, p=.0034. The four-stimulus condition RTs were longer than the two-stimulus condition for the choice task but not the simple task: task * stimulus, F(1,10)=293, p<.0001. The increase in RT due to number of stimuli was greater for auditory stimuli: modality * stimulus, F(1,10)=25.3, p=.0005. There was no significant difference in the RTs between auditory and visual oddball tasks. In order to determine whether each of the letter stimuli was processed similarly, a repeated-measures ANOVA was conducted with the factors: modality (auditory, visual) and letter, separately for the two choice and the four choice conditions. No significant interactions were found between modality and letter, suggesting the letters were equivalent.

Whereas the Falkenstein et al. dataset had no significant accuracy effects, in the present experiment the auditory tasks were easier than the visual tasks: modality, F(1,10)=6.29, p=.031. This was mostly because the error rate for the two-choice auditory task was significantly lower: modality * stimulus, F(1,10)=8.15, p=.0171. Accuracy of the oddball conditions was at ceiling (99% each).

Windowed ERP measures

Figure 1 displays the data we obtained in the standard oddball blocks. The stimuli in this experiment clearly elicited a standard parietal maximum P300 when used in a conventional oddball paradigm (see review by Fabiani et al., 1987). This data serves as a comparison point for examining the componentry of the simple and choice tasks (useful since the other conditions differ in a number of ways such as response requirements and probability structure). It is noticeable that the amplitude of this P300 was smaller when elicited by auditory stimuli than when elicited by visual stimuli; this observation is consistent with prior reports and is not an issue for concern (Johnson, 1989a, 1989b). Furthermore, the wave shape of the P300 suggests that there was an increased level of latency jitter (cf. Spencer, Abad, & Donchin, 2000) for auditory stimuli in this experiment. This is not surprising as the instant at which a voiced letter is identified relative to the physical onset of the stimulus is much more variable than when the letter is presented visually.

The data obtained in the replication of Falkenstein et al., (1994) are displayed in Figures 2 and 3, in which are shown the ERPs elicited by the stimuli in the two and the four stimulus conditions, for simple and choice responses. It is evident that, given the data presented in Figure 1, the ERPs appear to be characterized by a similar parietal positive P300, though the wave shapes do show the variations from the standard P300 format noted by Falkenstein and his colleagues. Thus, as noted in the figure, two positive peaks corresponding to Falkenstein's P-SR and P-CR can be observed. The P-SR and the auditory N1 appear to be smaller while the visual N2 appears to be larger, perhaps due to differences in stimulus characteristics. Before examining the componential structure of these waveforms we attempted to replicate Falkenstein's data analyses.

The smaller P-SR precluded reliable peak analyses of the sort conducted by Falkenstein and colleagues; roughly a third of the averages were categorized as being missing data by their criteria. Such an observation is consistent with prior studies which exhibit a small P300 due to the equiprobable nature of the target stimuli (Johnson, 1986) and a small P3a due to habituation with repeated presentations (Courchesne, 1978). We chose, however, to conduct a windowed amplitude analysis using the time ranges as previously described (Falkenstein et al., 1994), with the modification that the period of overlap was excluded: 350-425 ms for the P-SR and 485-700 ms for the P-CR. This modification was added to avoid injecting potentially subjective peak-picking into the procedure. The chief concern is to determine if the two primary effects replicated: 1) a modality-related topography change for the P-SR and 2) a latency increase with greater choice difficulty for the P-CR.

For the P-SR window, the amplitudes increased from anterior to posterior sites: F(2,20)=36.3, p<.0001, e=.691. As seen in Figure 2, there was an interaction between electrodes and modality such that the topography was fronto-central for the auditory stimuli and parietal-central for the visual stimuli, replicating the primary P-SR result: F(2,20)=8.4, p=.0095, e=.629. There was also a modality * task * electrode interaction for which the normalized analysis did not confirm the electrode effect: F(2,20)=16.0, p=.0019. As is true for the oddball data in Figure 1, it appears that the amplitudes were larger for the visual stimuli in the choice condition. As we noted, this difference is probably due to the greater variability in the onset of sensory detection of auditory stimuli (spoken vowels) than for the visual stimuli, causing more trial-to-trial variability in P300 latencies for the former. Such variability would cause the averaged P300 to be more spread out and hence lower in peak amplitude.

For the P-CR window, the only topographical effect to be confirmed by the vector normalization analysis was a frontal maximum topography in the simple condition and a posterior maximum topography in the choice condition: F(2,20)=6.8, p=.0209, e=.571. An additional effect whose topographical interaction was not confirmed was a larger response to auditory stimuli in the simple condition and a larger response to visual stimuli in the choice condition: F(2,20)=3.9, p=.0505, e=.790. Finally, an additional effect with an unconfirmed electrode interaction was a much larger amplitude for the 4-choice condition compared to the others conditions: F(2,20)=4.1, p=.0636, e=.566. This clearly reflects the shift of a greater portion of the P-CR into the P-CR window in the 4-choice condition seen in Figure 3, replicating the primary Falkenstein et al. (1994) P-CR result.

The oddball tasks were analyzed in a similar fashion, using the P-CR window. As expected, the rare targets produced a significantly larger response than the frequent standards: F(1,10)=76.6, p=.0290. There was a trend towards a larger response for the visual condition, much like for the P-CR: F(1,10)=4.0, p=.0728.

Principal Components Analysis

A parallel test (Dien, 1998) indicated that 11 factors should be retained from the initial spatial PCA, accounting for 85.5% of the variance. For simplicity's sake, the same number of factors was retained for all the temporal PCAs (the largest number indicated by any of the scree tests) since over-extraction is generally not a problem for ERPs (Dien, 1998; Wood, Tataryn, & Gorsuch, 1996). Since it was not possible to construct a noise average to carry out the parallel test for the temporal PCA step, a Scree test (Cattell, 1966) suggested that four factors would be appropriate for the temporal PCA step, with variance accounted for running from 75.5% to 88.7%.

When examining the late positivities, it is important to look for the presence of a contingent negative variation (CNV), a sign of pre-stimulus preparation (Brunia, 1993; Tecce, 1972). If the data are baseline corrected, since the baseline contains the CNV, it will misestimate the true zero. As the CNV starts resolving, it may appear as a developing positivity rather than as the disappearance of a negativity. Close examination revealed no evidence for a CNV in this dataset.

As seen in Figure 4, Spatial Factor 1 and Spatial Factor 2 appear to correspond to Falkenstein's P-CR and auditory P-SR respectively. Next to these factors we display the topographical maps of the P300 and the P3a factors from a conventional auditory Novelty P3 experiment with complex environmental novel sounds, using the same PCA procedures (Dien et al., 2003). As can be seen, the factor topographies appear quite similar. The "P-SR" and the P3a factor topographies correlated at r=.86 (when the 129 channel values are computed as the observations), which suggests they are substantially the same. Unfortunately, an inferential test for evaluating the similarity of the topographies is not available, to our knowledge.[2] Likewise, the "P-CR" and the P300 factor topographies correlate at r=.88. Thus far the results are in accord with both accounts. This observation is further strengthened by the fact that the conditions differed in regard to both stimulus probabilities and in response requirements.

In a spatiotemporal PCA, the temporal factors generated from a spatial factor all have the identical scalp topography of the original spatial factor. For this reason, the temporal decomposition of the spatial factors is not pertinent to the issue of whether a factor with a Cz maximal distribution can be identified. For methodological reasons, however, it is of interest to examine how the temporal PCA dealt with the latency jitter that both accounts indicate should be present. In the spatiotemporal PCA procedure, the initial step is a spatial PCA, which yields virtual waveforms that are quite capable of representing latency changes. As can be seen in Figure 5, the virtual waveform of the first spatial factor has largely accounted for the entirety of the grand average at Pz. The succeeding temporal PCA step provides information that helps the researcher determine whether a given spatial factor represents multiple components. Since a temporal PCA, by definition, defines a factor by a fixed waveform with a particular latency (described by its factor loadings), it accounts for latency changes via multiple factors. It is therefore incumbent upon the investigator to determine whether temporal factors are due to separate components or latency changes.

In the present analysis, the succeeding temporal PCA split the majority of the first spatial factor into four temporal factors. As seen in the figure, it has accomplished this task by modeling the virtual waveform in the two conditions as a mix of the four temporal factors. Using the PCA reconstruction procedure, we can observe how the summation of the four temporal factors (S1T1 through S1T4) mostly accounts for the virtual waveforms of S1, which in turn mostly accounts for the original grand average data. While the PCA has indeed been able to accommodate the latency shift in this fashion, it did result in none of the four factors having significant effects: modality (auditory, visual), task (choice, simple), stimulus (2-choice, 4-choice).

While the temporal PCA step is helpful for separating components confounded by a spatial factor, it is clearly not an efficient approach for analyzing latency changes of a single component. Since the temporal PCA did not provide clear evidence for multiple components within the P-CR time period, a latency analysis was conducted on the spatial factor's virtual waveform. The factor scores representing the window 200-600 ms were subjected to a peak latency analysis. Although both the P300 and the P-CR accounts would have predicted a latency shift between the two and four choice conditions, the only significant effect was a longer latency for the choice task of 379 vs. 305 ms: task, $F(1,10)=13.3$, $p=.0045$. No effect was found for number of stimuli.

Both the traditional P300 account, and Falkenstein's proposed P-CR account, predicts that the number of stimuli should affect latencies in the choice conditions. The fact that this prediction was not confirmed by our data is troublesome for both views. Examination of the factor waveforms seen in Figure 5 reveals that although a shift is visible, the peak has not shifted. This result could be consistent with the claim that there is a fixed latency P-SR (accounting for the dominant peak) and a shifting P-CR (accounting for the lesser movement of activity). Given the evidence presented thus far, a simpler interpretation is that part of the P300 process has been prolonged, resulting in the enlargement of the descending slope in the 4-choice condition, without affecting the latency of the peak time point. The P300 waveforms are consistent with a P300 that has a larger amplitude in the 4-choice (.25 probability) condition than in the 2-choice (.50 probability) condition but more spread out due to latency jitter. A centroid measure is better suited for measuring latency in this situation.

The centroid was calculated for the range of t time points in the window of interest, from 200 to 600 ms. Using this centroid measure on the reconstructed data accounted for at Pz by SF1, the expected interaction between task and stimulus number was observed: F(1,10)=6.1, p=.0334. This interaction was due to a longer centroid latency for 4-stimuli in the choice task (462 vs. 428 ms: F[1,10]=26.4, p=.0004) but not the simple task (F[1,10]=2.7, p=n.s.). In contrast, the peak latency difference was not significant even as a planned contrast (386 vs. 372 ms: F[1,10]=1.4, p=n.s.). Additional support for a latency shift, rather than the addition of a new component, was the lack of a significant difference in windowed mean amplitude, even for the planned contrast of 4-stimuli choice vs. 2-stimuli choice conditions (2.0 vs. 1.6 μv: F[1,10]=.70, p=n.s.).

Figure 6 shows how the spatiotemporal PCA decomposed the putative P-SR and P-CR for the three major factors (the P3a factor and the P3 factors S1T2 and S1T3 factors). The bar charts suggest that all the simple and choice conditions contain P300 activity to the extent that there were no statistically significant differences. They also indicate that there was a substantial difference between auditory stimuli (frontal positive) and visual stimuli (frontal negative): modality, F(1, 10) = 16.8, p=.0021. This negativity reflects the enhanced N2 that is apparent for the visual stimuli, indicating that the frontal factor incorporated the N2 in addition to the P3a, which suggests either that the N2 is too similar to disambiguate or that it is part of a biphasic response with the P3a and thus has the same topography.

For the oddball conditions, the ANOVAs reveal a different story. In analyses with the design modality (auditory, visual) * probability (frequent, rare), the P3a factor was larger for rare targets regardless of modality: probability, F(1,10)=7.4, p=.0215. The early P3 factor was larger for visual stimuli (modality, F[1,10]=9.8,p=.0108) and for rare stimuli (probability, F[1,10]=14.2, p=.0037). The late P3 factor was also larger for visual stimuli (modality, F[1,10]=49.8, p<.0001) and for rare stimuli (probability, F[1,10]=53.4, p<.0001), especially visual stimuli (modality * probability, F[1,10]=11.5,p=.0068). Since both P3 latency factors respond in the same direction to modality and probability, these effects do not represent a latency shift but rather a simple amplitude change.

DISCUSSION

Falkenstein and colleagues (1994) suggested that there are two late positive components: 1) a P-SR whose latency is stimulus-locked and whose topography is modality dependent and 2) a P-CR whose latency is response-locked and whose topography is modality independent. Such a finding would be important because it could require a reanalysis of the large body of P300 studies. The present analysis does not support this conclusion and strongly suggests that a relabeling of the existing P3a and P300 components is unnecessary. The PCA produced evidence for only two components whose topographies correspond to previously characterized P3a and P300 topographies. For this reason, we do not believe there are sufficient grounds to identify yet another component to be labeled “a visual P-SR” that is distinct from the P300/P-CR and the P3a/ auditory P-SR. Notable by its absence in the present analysis is the Positive Slow Wave, whose nature and whose eliciting conditions remain uncertain. Still remaining is the question of the nature of these two components, whether termed the P300 and the P3a or the P-CR and the auditory P-SR, respectively.

The primary test of the two accounts is whether evidence can be seen for an additional visual P-SR with a centro-parietal distribution. According to the Falkenstein et al. account, there should be a visual P-SR present in the simple task but no P-CR while the P-CR should be present with the P-SR only in the choice task. No evidence could be seen for separate visual P-SR and P-CR components. While one cannot rule out the possibility that two such components with similar topographies might have been subsumed into the same spatial factor (such conflations being the motivation for the second temporal PCA step), it does suggest matters may not be as clear-cut as described by the P-SR/P-CR account.

To consider the theoretical arguments regarding the nature of these two components, it is first necessary to review the general cognitive model as seen through the lens of the ERP literature. When discussing the P300, it has been convenient to discuss information processing as a two-stage process, consisting of stimulus evaluation and response execution. It is useful to recall the historical context in which the early studies of P300 latency were conducted. In the early 70's several investigators (e.g., Donald, 1979) were troubled by the common observation of a dissociation between the latency of P300 and RT. As RT was taken as a standard measure of information processing time it seemed logical to expect P300 latency, when measured over the trials in an experiment, to be correlated with RT. The dissociation was taken as evidence that P300 cannot be a manifestation of information processing activities. Donchin and his colleagues (Donchin, 1982; Kutas & Donchin, 1978) suggested a more benign, and much more useful, interpretation of the dissociation by noting that RT represents the summation of the durations of several different information processing activities and that

P300 latency may index only some of these activities. The dissociation made P300 latency a useful tool in "augmenting mental chronometry" (Kutas et al., 1977). They were able to demonstrate that P300 latency varied with categorization and processing difficulty, while it was largely independent of the RT variance that was introduced by requiring incompatible responses (McCarthy & Donchin, 1981). It was this dissociation that lead to the suggestion that P300 latency indexes the duration of "stimulus evaluation" processes while it was relatively unaffected by response execution processes.

In this framework, the P300 has provided a useful dependent variable because it seems to index the end of the stimulus evaluation period (Duncan-Johnson, 1981; Kutas et al., 1977), whereas RTs reflect both stimulus evaluation and response execution stages. While this has been a useful approach to the dilemma presented by the Latency/RT dissociation, it is evident that the variances in question reflect more than a two-stage process (Sternberg, 1969; Teichner & Krebs, 1974). Indeed, the nature of the processing stages is at the core of the dispute over the nature of the P300/P-CR.

We suggest that the ERP literature clearly distinguishes at least four general stimulus-related steps in simple discrimination tasks, each encompassing multiple processes:

1) Stimulus Registration. This is the simple registration that a stimulus event has occurred and is marked by the exogenous sensory components, such as some of the P1 and N1 components for auditory and visual stimuli.

2) Stimulus Selection. This is the determination that a stimulus event is part of a task-relevant sensory channel, marking it for further analysis. In the auditory domain, this determination is marked by the Processing Negativity (PN), a frontal negativity that is enhanced for attended stimuli (Näätänen, 1982, 1992). For example, in an oddball paradigm, if the target is left ear low tones, all stimuli presented to the left ear (target or

not) will produce an enhanced PN, compared to right ear stimuli. The PN is a separate component from the auditory N1 (Dien, Tucker, Potts, & Hartry, 1997; Woods & Clayworth, 1987). Similar PNs (or Selection Negativities) have been reported in the visual domain (Eimer, 1999; Harter & Aine, 1984; Hillyard & Munte, 1984). Behaviorally, evidence for an initial broad selection for relevance has been found in the phenomenon of attentional control settings (Folk, Remington, & Johnston, 1992) wherein a color singleton distractor will only capture attention if the target is defined by its color.

3) Stimulus Identification. This is the final determination of a stimulus identity or type. Although there does not seem to be a generalized ERP component associated with this step, the visual N2 appears to be a marker for this process for simple discriminations (Ritter, Simson, Vaughan, & Macht, 1982) while the N400 (Kutas & Hillyard, 1980) might be considered a marker for this step for semantic stimuli. This is the stage associated with the P-SR by Falkenstein and his colleagues.

4) Stimulus Categorization. This is a post-identification process whereby stimuli are classified into a task-relevant category. Donchin and colleagues have argued that the P300 is a manifestation of a process triggered by the system's recognition that there is a need for "context updating" (Donchin & Coles, 1988) whereby the probability expectations for stimuli, as categorized into task-relevant groups (Johnson & Donchin, 1980), are revised.

It should be noted that the "serial" presentation of this model does not imply that the system operates in a serial fashion. There is ample evidence in support of the existence of a "continuous flow" (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Osman, Bashore, Coles, Donchin, & Meyer, 1992) between these different phases of processing and the response execution processes. Yet within this framework, there is no question that the P300/P-CR manifests processes that require the completion of a substantial measure of Stimulus Categorization. The question then is whether this component also manifests even later processes at the Response Selection stage. We argue that in the study reported by Falkenstein et al. (1994), the choice complexity manipulation fails to distinguish between stimulus categorization and response selection stages. The increase in the number of letters increases latency in the choice task because it increases the difficulty of categorizing the stimulus, not because it increases the difficulty of choosing which finger to respond with. It is for this reason that the experiments by Donders, who pioneered this type of analysis, used as his simple RT paradigm a task in which the subjects would respond to only one of the possible stimuli. In this fashion, he avoided confounding response selection with stimulus discrimination (cf. Teichner & Krebs, 1974). In order to make the case that the P300/P-CR latency reflects response selection time, Falkenstein and his colleagues need to use a similar procedure. As already noted (Kutas et al., 1977; Magliero et al., 1984; McCarthy & Donchin, 1981), when stimulus categorization and response selection are properly differentiated, the P300 (or P-CR as termed by Falkenstein and colleagues) mainly correlates with the stimulus categorization time, not with response selection time, although a small percentage of the P300 latency variance does appear to be correlated with response selection (Magliero et al., 1984).

This concern with the Falkenstein et al. (1994) paradigm has been noted elsewhere (Verleger, 1997 p. 142) and defended on the basis that latency of naming letters and words is not dependent on the number of target stimuli in contrast to other types of stimuli, implying that this manipulation would have to be affecting the response selection stage. However, the three papers cited do not support this position. The first (Fraisse, 1969) examines the effects of discriminability and stimulus type rather than stimulus set size. The second (La Heij & Vermeij, 1987) used latency onset of vocal naming, a measure that is known to have important differences from manual responses (e.g., Seidenberg, Waters, Sanders, & Langer, 1984). It is quite reasonable for the RT effect to be arising from post-lexical verification processes much like those found in manual lexical decision studies. The third paper examines the effects of physical stimulus size rather than number of stimuli (Theios & Amrhein, 1989). The argument that the P300/P-CR must reflect response selection because it is absent in the simple response condition is not compelling since it could simply be the parietal-central portion of what they labeled the P-SR. The modality dependent topography could be due to the overlapping P3a. The lack of a latency shift in the P300 portion of the "P-SR" with increased stimulus set size could merely reflect the ease of stimulus categorization in a simple detection task (where there is only one category). Given the vast number of P300 studies supporting the premise that the P300 reflects primarily stimulus evaluation time, (or more specifically, stimulus categorization time) the onus for demonstrating otherwise remains with Falkenstein and his colleagues.

The present findings do provide some additional information on the nature of the P3a. When the P3a was first reported, it was found to be elicited specifically by non-target distractor stimuli, rather than targets (Courchesne et al., 1975). Investigators have since assumed that one of the defining characteristics of the P3a is that it is elicited only by highly deviant distractors. However, in a previous study we found that a small P3a is indeed elicited by rare target stimuli in the oddball task (Spencer et al., 1999a, 2001). The present data confirm this finding, and demonstrate that the P3a can be elicited by target stimuli in general, which are not necessarily confined to the oddball paradigm. The evidence that target stimuli, as well as non-target distractors, can elicit the P3a (see also Gaeta, Friedman, & Hunt, 2003) suggests that it is necessary to revise previous views of the functional significance of the P3a. Four principal accounts of the P3a have been proposed in the literature:

1) The Novelty Account. The most commonly cited view is that the P3a is part of the general orienting response to "unexpected novel stimuli" (Daffner, Mesulam, Scinto, Cohen, Kennedy, West, & Holcomb, 1998; Fabiani & Friedman, 1995; Knight, 1996). While this is a reasonable interpretation of the early P3a literature, it is agnostic as to the

cognitive significance of the component. In the current experiment, the spoken letters are not at all unexpected, as they are target stimuli (although they may be unusual in the context of sitting in front of a computer). The present experiment therefore suggests that unexpectedness is not at all necessary to produce the P3a (although it may increase it, cf. Verleger et al., 1994). Indeed, in young adult subjects unusual environmental sounds produce P3a's that habituate as subjects become familiar with them (Fabiani & Friedman, 1995). Additionally, in their simple three-stimulus paradigm, Polich and colleagues (Comerchero & Polich, 1999; Katayama & Polich, 1998) and others (Goldstein et al., 2002) have shown that it is possible for even a very simple stimulus to produce a P3a as long as 1) the deviant stimulus is easily distinguished from the target and the standard, and 2) the target and standard stimuli are difficult to discriminate. “Unexpectedness” and “novelty” are therefore insufficient to explain the data, but stimulus salience does appear to be an important factor controlling P3a amplitude.

2) The Attention Shift Account. A more specific view is that the P3a reflects a shifting of attention, perhaps as part of an orienting response (Katayama & Polich, 1998; Näätänen, 1992). While highly deviant stimuli that elicit the P3a could indeed induce a shift of attention to the stimulus stream from the primary task (e.g., reading) in a typical mismatch negativity paradigm (see also, Escera, Alho, Winkler, & Näätänen, 1998), it makes little sense to say that there is a shift of attention in experimental paradigms in which all the stimuli in the sequence are in fact attended, as in a typical novelty oddball task. The evidence from this study and others (Spencer et al., 1999a, 2001) that target stimuli elicit the P3a further weighs against the attention shift hypothesis.

3) The “Inhibition Account.” A third hypothesis regarding the functional significance of the P3a relates it to another late ERP component with a positive polarity and fronto-central scalp topography: the “No-Go P3” (Pfefferbaum et al., 1985). The similarity in topography and morphology between the P3a and the No-Go P3 suggest that

these components could in fact be identical. Stimuli that elicit the P3a often are associated with false alarms (e.g., Comerchero & Polich, 1999; Goldstein et al., 2002), so one possibility is that the P3a reflects a response-inhibition process, as has been proposed for the No-Go P3. The presentation of an infrequent, highly deviant distractor stimulus could induce subjects to “jump the gun” and initiate a target response that would need to be suppressed. However, the present data argue against this account because target stimuli elicited the P3a. Also, the P3a is found in oddball tasks in which the response requirement is to keep a mental count of the targets, rather than to make an overt response.

4) The "Task Switch" Account. A recent paper (Barcelo, Periañez, & Knight, 2002) involved a computerized variant of the Wisconsin Card Sort Task (WCST) wherein subjects were instructed to sort stimuli based on either color, number, or shape. The basis for the sorting could change unpredictably and would be signaled by a simple feedback tone (1000Hz for shift and 500Hz for stay). The shift tones elicited a robust P3a. This observation is not consistent with the Novelty account or a stimulus salience account since the stimuli were not highly deviant in the context of the experiment. The attention shift account cannot explain this observation since all the stimuli are attended. Furthermore, the inhibition account cannot account for this finding since no response is required to the feedback. However, in Barcelo et al.’s design, the stimuli calling for a task shift also provided “negative feedback” in that they indicated to the subjects that their choice on the current trial is erroneous. Furthermore, the “task shifting” trials were quite rare events (occurring at the rate 1/7th of the trials). Hence, their identification of the P3a (or P3a) as a manifestation of task shifting is not compelling.

Whatever cognitive process is reflected by the P3a, in terms of the general four-stage model described earlier, it would appear that the P3a operates at the Stimulus Selection stage. While the PNs are larger to all stimuli in the attended channel, the P3a appears to be larger to stimuli that deviate highly from the attended channel (Katayama & Polich, 1998). Why the P3a would then be partially elicited by target stimuli is unclear. One hypothesis, which would require further study, is that the "attended channel" is defined by the contents of working memory, following the logic of Fabiani and colleagues (Fabiani & Friedman, 1995). The representation of rare targets would tend to decay more quickly than that of frequent standards, tending to put them outside of the "attended channel." Highly practiced visual stimuli, like letters, would tend to be easier to retain in working memory than the very idiosyncratic auditory letters. Perhaps this is the reason why the visual stimuli did not generally produce a P3a. The exception to the absence of P3as to visual stimuli was the rare targets in the visual oddball condition where repeated presentations of the frequent standard might interfere with the active representation of the rare target. Likewise, the main exception for the appearance of a P3a to auditory stimuli is the frequent standard in the auditory oddball condition. In this case, frequent presentations would facilitate maintenance of its representation despite the difficulty of the stimulus. The anomaly for this account is the auditory stimuli in the simple 2-choice condition, which also did not produce a P3a. Further studies will be required.

In part, the theories that attempt to account for the functional significance of the P3a present a confusing picture because they do not distinguish between an enumeration of the antecedent conditions of the component and a theoretical account of the functional significance of the component. As Donchin (1981) has noted the enumeration of the antecedent condition, that is a determination of the conditions that are necessary and sufficient to assure the elicitation of a component, is a crucial stage in developing a theory of a component. However, even a complete listing of these conditions does not constitute a theory of the component as there is no unique and necessary relationship between the antecedent conditions and a hypothesis about the functional significance. Furthermore, a hypothesis about the functional significance of a component is not tested merely in terms of the degree to which it provides a post-hoc account for the antecedent conditions. Any theory of a component must generate predictions about the consequences of the component (see also Donchin & Coles, 1988) that can be tested empirically. The above accounts are primarily descriptions of antecedent conditions. A full description of the P3a will need to propose the ultimate functional significance of the P3a process and describe how the various antecedent conditions might relate to the ultimate goal of the process, such that predictions might be made about additional antecedent conditions.

Insufficient information has been obtained at this point to confidently endorse any one theoretical account of the P3a as of this point. Further studies will be required to determine the nature of the P3a process and its eliciting conditions. We can say that sufficient evidence has accumulated that "Novelty P3" may be a misnomer and that it would be appropriate to simply term it the "P3a", by which we mean the frontal aspect of the response elicited by novel and other stimuli. Likewise, continuing experiments will be required to better determine the nature of the other late positive waves. As for the interpretation of P300 latency, it can be concluded that the studies by Falkenstein and his colleagues do not necessitate a reevaluation of the P300 latency measure, although these studies do reinforce the necessity for taking overlapping components into account (cf. Fabiani et al., 1987; Gratton, Coles, & Donchin, 1989).

Falkenstein and colleagues are, however, engaged in a potentially important investigation of how the P3a and the P300 relate to stages of processing. We confirmed their interesting finding of a frontal component in the auditory condition, although we disagree regarding its identity. Our data also confirm their reports of interesting differences between the simple and choice tasks and how they relate to the number of stimuli. Once the conceptual and componentry issues are addressed, we look forward to their future findings. As technological and methodological advances continue, it will be necessary to revisit previous conclusions to update and extend them, as has been done in the present report.

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The preparation of this manuscript was partially supported by National Institutes of Mental Health grants MH11751 and MH19554 and a Louisiana Board of Regents Research Competitiveness Subprogram grant (LEQSF-RD-A-27).

We thank the editor Ray Johnson, Jr., Michael Falkenstein, and two blind reviewers for their extensive comments and suggestions.

Footnotes

1. The PCA Toolbox (version 1.06) differs from the PCA procedure we reported previously in three details, none of which has a notable impact on the present analyses: 1) it variance-corrects the factor scores but does not mean-correct them, preserving mean differences in the factor scores; 2) it can turn off the Kaiser correction, which can sometimes have the undesirable effect of equalizing the contribution of the variables (Dien, Beal, & Berg, submitted); 3) it directly rotates the factor scores (Möcks & Verleger, 1991), which makes it possible to apply separate temporal PCAs to each spatial factor, which may allow for more subtle time course distinctions to be applied to each spatial factor. Direct rotation of factor scores makes it possible to apply separate PCAs because otherwise factor scores have to be generated by an equation that uses a generalized inverse to estimate the inverse of the relationship matrix; this estimation procedure results in collinearity errors when applied to a dataset in which there were more variables than observations, which is typically the case when the factor scores from each spatial factor is temporally factored separately.

PCA decomposes data matrices into two matrices (factor loadings and factor scores). The PCA Toolbox reconstructs the original data matrix by multiplying these two matrices together (and rescaling the standardized factor scores back to microvolts). A single factor can be evaluated by reconstructing just the portion of the data matrix accounted for by the one factor. For a conventional PCA, one multiplies the factor loadings by the mean of the appropriate factor scores and the standard deviation for each variable (Dien et al., 1997; Möcks & Verleger, 1991). For an oblique rotation, the factor pattern matrix is most appropriate since the factor structure matrix includes influences from correlated factors.

In the extension of the reconstruction procedure to the spatiotemporal PCA, presented herein for the first time, one must first multiply the factor scores of the temporal factor by the spatial factor loadings and by the standard deviations of the variables of the temporal step (the factor scores positioned as time points). This multiplication reconstitutes the portion of the spatial factor scores accounted for by the temporal PCA factor of interest. This is then multiplied by the spatial factor loading and by the standard deviations of the spatial variables (the channels). The full equation to generate the microvolt value for a specific time point t and channel c for a spatiotemporal PCA is: L1 * V1 * L2 * S2 * V2 (where L1 is the spatial PCA factor loading for c, V1 is the standard deviation of c, L2 is the temporal PCA factor loading for t, S2 is the mean factor scores for the temporal factor, and V2 is the standard deviation of the spatial factor scores at t.

2. A Pearson's correlation is not appropriate because the channels do not represent independent observations and using the full degrees of freedom would unduly inflate the significance level. A creative procedure has been introduced to address this issue by correcting the degrees of freedom with the Geisser-Greenhouse epsilon (Hamm, Johnson, & Kirk, 2002) but unfortunately it may be doubted. The Geisser-Greenhouse is designed to address violations of the assumption of sphericity, which is an extension of the assumption of equal population variances when comparing groups (Maxwell & Delaney, 1990 , see footnote 5, chapter 11), rather than the assumption of independent observations. The size of the G-G epsilon will therefore be unrelated to the extent of non-independence in the data. In other words, the G-G epsilon is a solution for an entirely different problem than non-independence of observations.

TABLE ONE

	Auditory			Visual		
	2	4	D42	2	4	D42
SR	244 (38)	250 (34)	6	235 (31)	225 (27)	-10
CR	385 (24)	479 (21)	94	350 (24)	435 (26)	85
(%)	6.4	15.5		15.2	19.4	
Oddball	280 (32)			291 (37)		

Table Legends

1) Behavioral data. Mean reaction times in milliseconds for each condition. Standard deviations in parentheses. D42 columns show the difference between the 2 and 4 choice conditions. The % row displays the error rate in the choice tasks. Reaction time data for the oddball condition is for the rare targets only (since no response was required for the standards).

Figure Legends

1) Grand average waveforms for the oddball conditions.

2) Grand average waveforms for the simple conditions.

3) Grand average waveforms for the choice conditions.

4) Scalp topographies of P-SR, P-CR, P300, and Novelty P3 factors. The portion of the grand average accounted for by each factor was reconstructed and then plotted as an overhead view with the nose facing upwards. The P300 and Novelty P3 factors are drawn from Dien, Spencer, & Donchin (in press). The time point chosen for each dataset corresponds to the peak of the P-SR factor and the Novelty P3 factor respectively. The P-SR and P-CR represent the auditory simple response 2-choice condition and the P300 and Novelty P3 represent the novel stimulus condition.

5) Factor waveforms of the P-CR. The waveform for the grand average at Pz is first displayed, followed by the spatial factor (S1) that accounted for the P-CR topography. Below these waveforms are the four temporal factors that the spatial factor was split into (along with their peak times). Finally, the summation of the four temporal factors is displayed on the right. Discrepancies between the summated waveforms and the original spatial waveform are due to variance dropped at the temporal PCA step when four factors were retained.

6) Factor Bar Charts. The bar charts indicate the microvolt value for the spatiotemporal factors at the peak time point at the focal electrode site (largest absolute mean amplitude that is not a midline or periocular electrode - the former in case laterality analysis is desired and the latter since they are more likely to be contaminated by eye artifacts). The Novelty P3 factor has a peak time of 316 msec and a focus just to the right of Fz. The P3

factors have a focus just to the right of Pz and peak times of 340 and 432 msec. The labels below the bars denote the different conditions in the experiment.

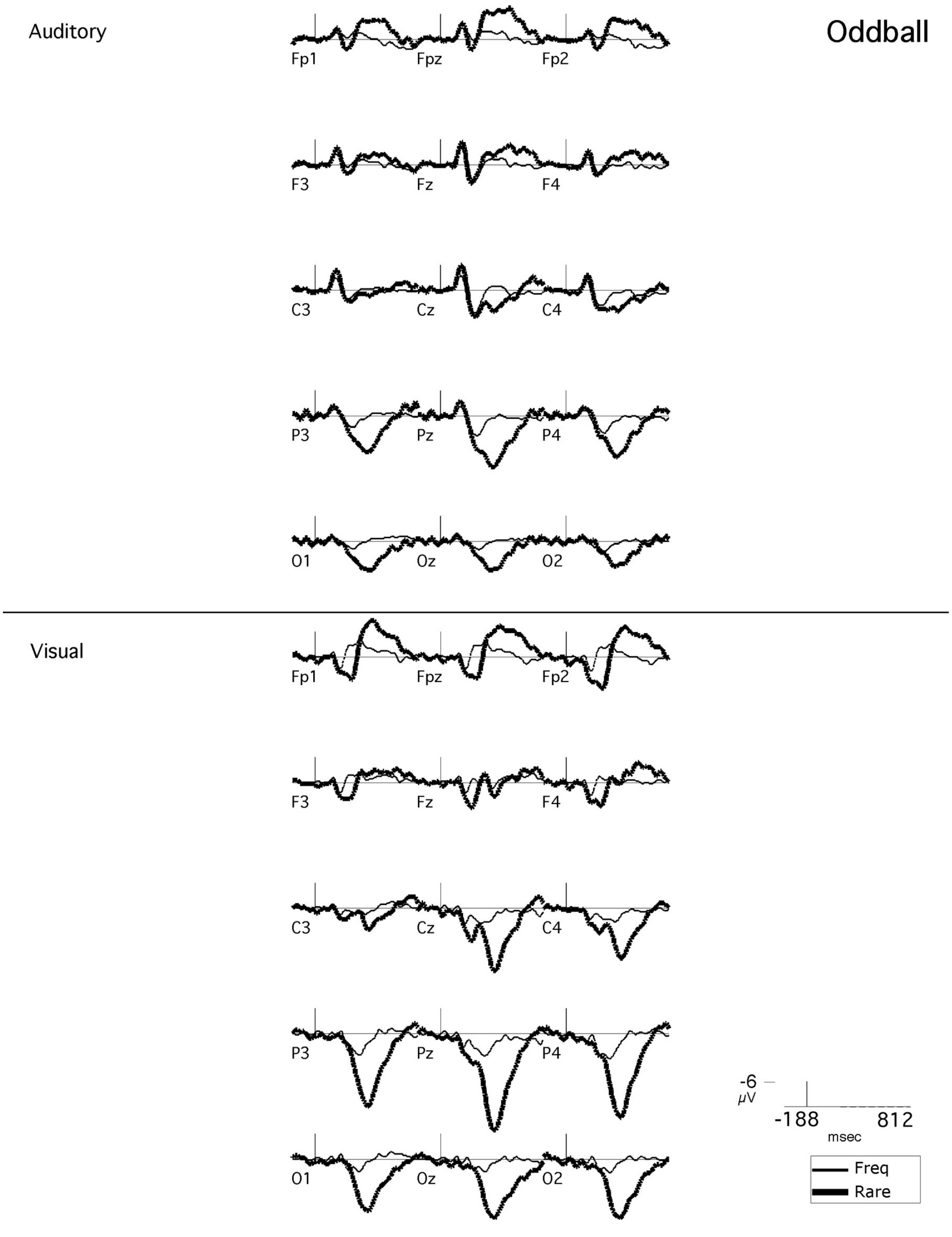

Auditory
Oddball
Fp1
Fpz
Fp2
F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
O1
Oz
O2
Visual
Fp1
Fpz
Fp2
F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
O1
Oz
O2
-6
µV
-188
812
msec
Freq
Rare

Figure 1

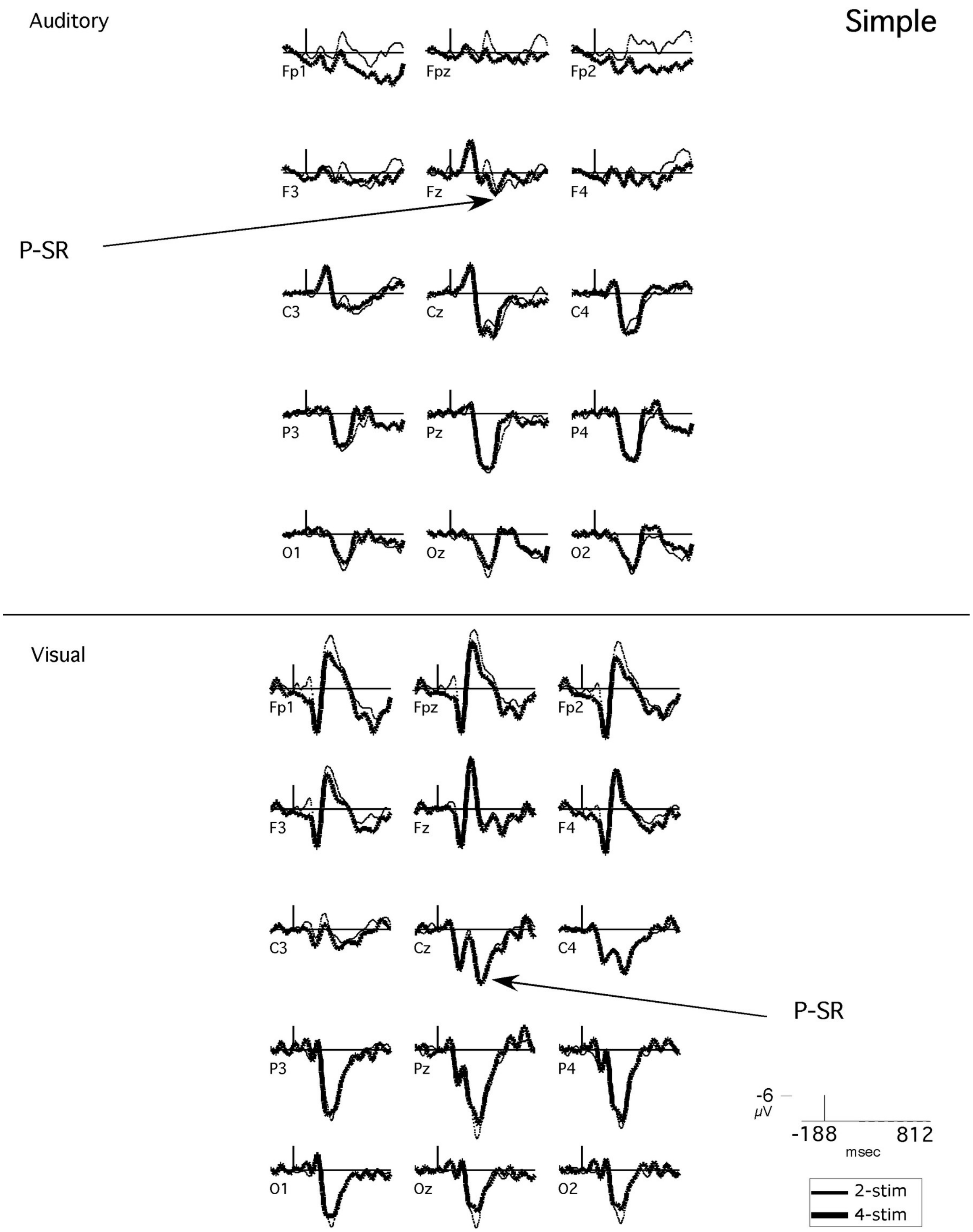

Auditory
Simple
Fp1
Fpz
Fp2
F3
Fz
F4
P-SR
C3
Cz
C4
P3
Pz
P4
O1
Oz
O2
Visual
Fp1
Fpz
Fp2
F3
Fz
F4
C3
Cz
C4
P-SR
P3
Pz
P4
-6
μV
-188
812
msec
O1
Oz
O2
2-stim
4-stim

Figure 2

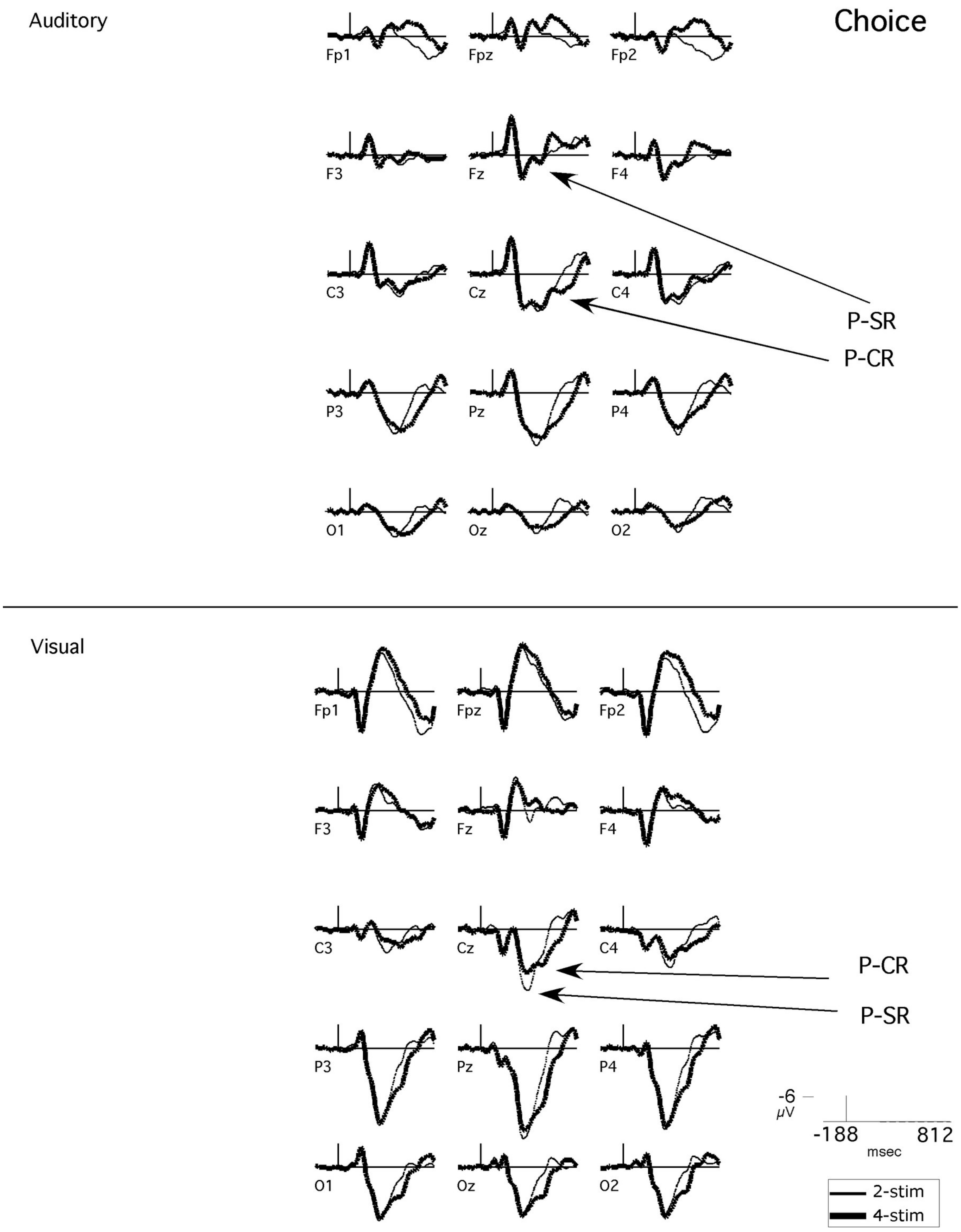
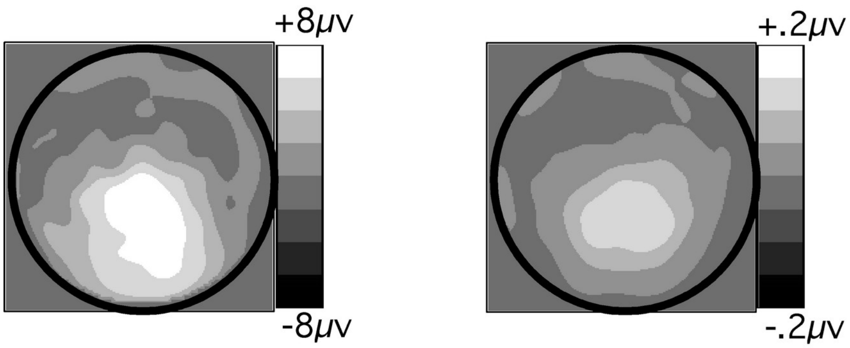
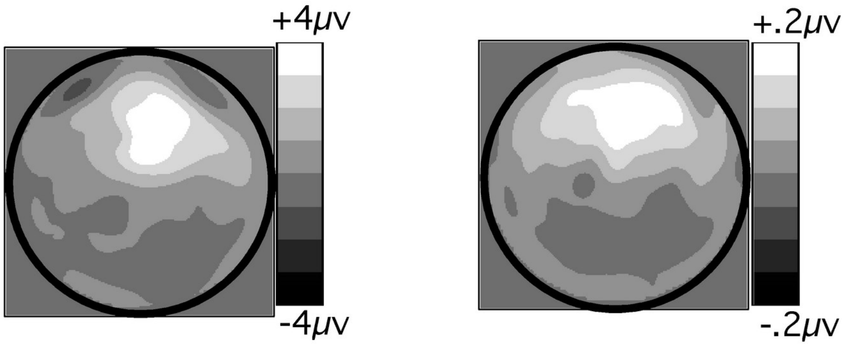

Auditory
Choice
Fp1
Fpz
Fp2
F3
Fz
F4
C3
Cz
C4
P-SR
P-CR
P3
Pz
P4
O1
Oz
O2
Visual
Fp1
Fpz
Fp2
F3
Fz
F4
C3
Cz
C4
P-CR
P-SR
P3
Pz
P4
O1
Oz
O2
-6
μV
-188
812
msec
2-stim
4-stim

Figure 3



P300 Factor P-CR Factor



Novelty P3 Factor P-SR Factor

328 ms 316 ms

Figure 4

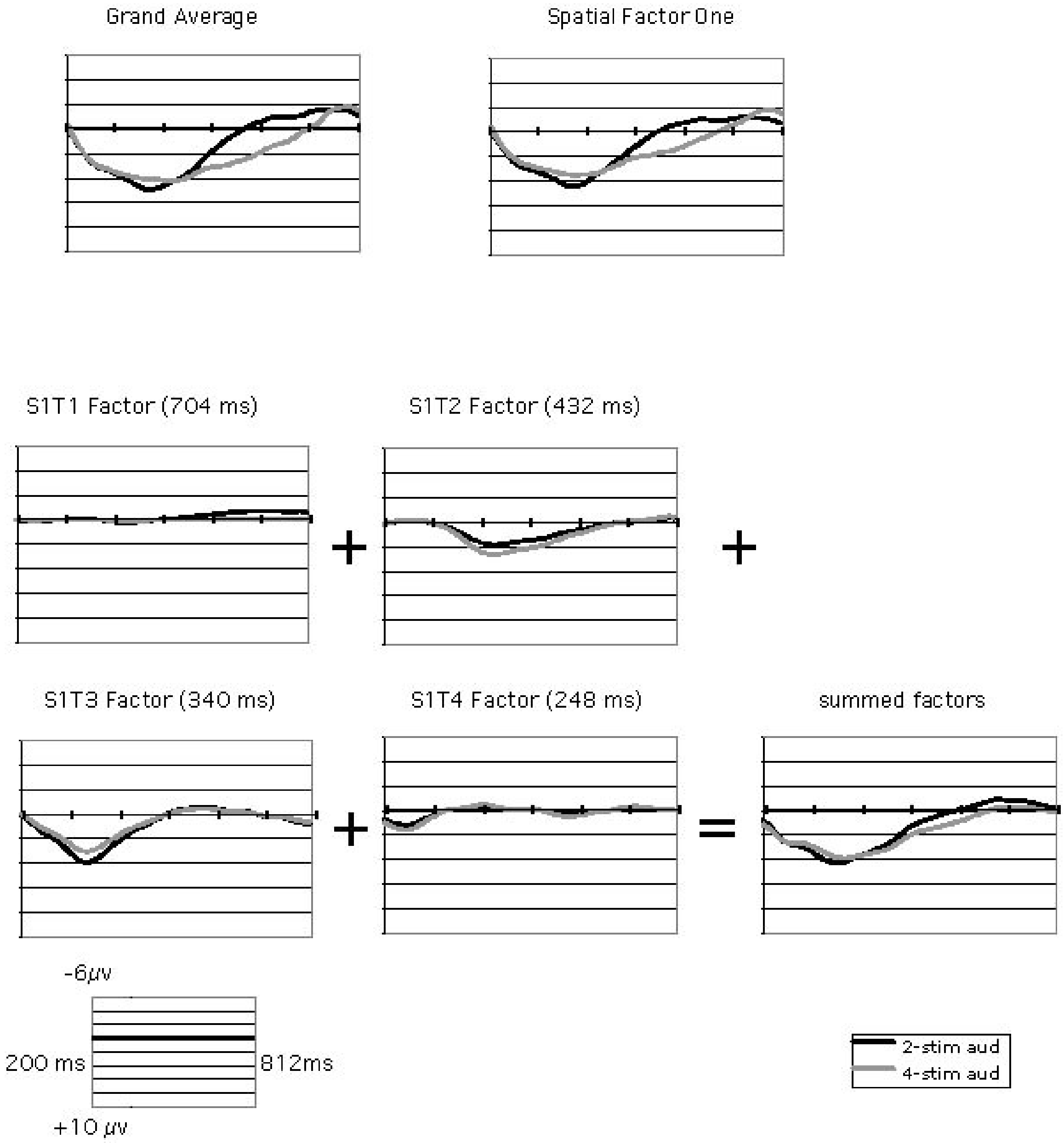
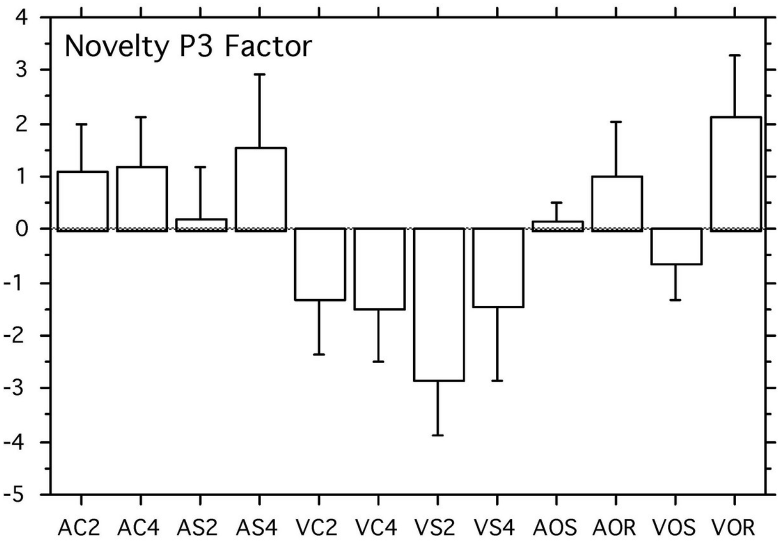
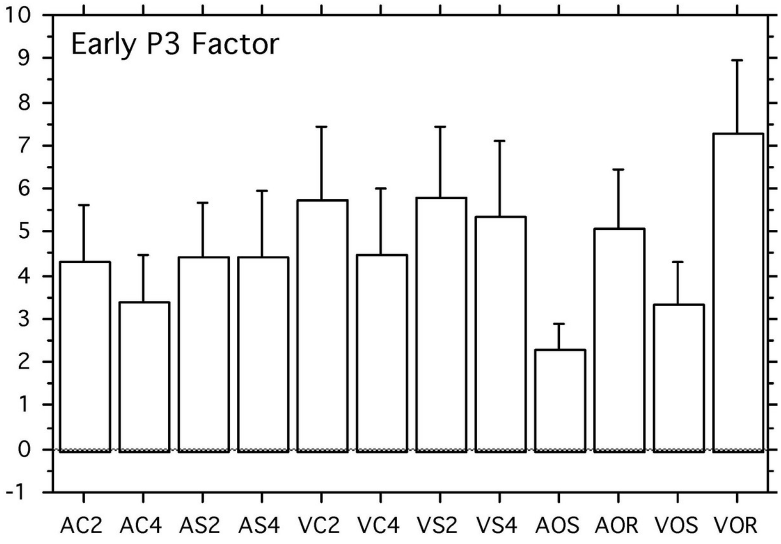

Grand Average
Spatial Factor One
S1T1 Factor (704 ms)
+
S1T2 Factor (432 ms)
+
S1T3 Factor (340 ms)
+
S1T4 Factor (248 ms)
=
summed factors
-6μv
200 ms
812ms
+10 μv
2-stim aud
4-stim aud

Figure 5


Novelty P3 Factor
4
3
2
1
0
-1
-2
-3
-4
-5
AC2 AC4 AS2 AS4 VC2 VC4 VS2 VS4 AOS AOR VOS VOR


Early P3 Factor
10
9
8
7
6
5
4
3
2
1
0
-1
AC2 AC4 AS2 AS4 VC2 VC4 VS2 VS4 AOS AOR VOS VOR

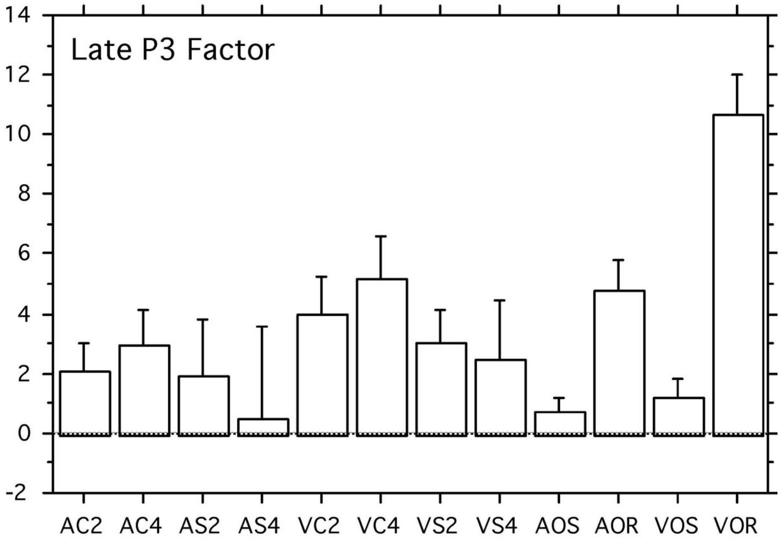

Late P3 Factor
14
12
10
8
6
4
2
0
-2
AC2 AC4 AS2 AS4 VC2 VC4 VS2 VS4 AOS AOR VOS VOR

Figure 6